Wind-solar-storage trade-offs in a decarbonizing electricity system

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Exploring cost-effective wind-solar-storage combinations to replace traditional fossil-fuelled power generation without compromising grid stability becomes crucial in a decarbonizing electricity system. We use Pareto frontiers to systematically evaluate the trade-offs between the annualised cost and reliability of different wind-solar-storage energy combinations to meet future electricity demand of a renewable rich state, Karnataka in Southern India. Pareto frontiers can characterize efficient solutions to multi-objective problems where it is not possible to improve one objective without worsening the other. Depending on the priorities, points on the Pareto frontier can be chosen.

The simulated scenarios consider an estimated increase in the demand for electricity, as well as varying base generation (Figure 1) and supply-side flexibility from hydropower and fossil fuels. We use hourly demand data, estimate the impact of battery charging and discharging on battery lives, and simulate generation based on hourly weather reanalysis data. In the context of declining base generation and limited flexibility in the state electricity grid, the reliability of meeting demand is limited by the allowed generation curtailment. We show that adding battery storage capacity without concomitant expansion of renewable generation capacity is inefficient.

Even with sufficient battery storage, a fully decarbonized grid with limited flexibility can achieve roughly 63% reliability by maintaining wind-solar installations within the officially recognized renewable potential. It would be costly and necessitate big wind-solar projects that surpass officially assessed potential (constrained by land allocation) in order to achieve 99% grid reliability. A completely decarbonized grid (in the absence of any base generation) with 6 GW of flexible generation and allowing for 30% annual curtailment of renewables would result in grid reliability of around 93%. The results emphasize how critical it is to do a fresh examination of curtailment thresholds, renewable energy potential, and demand-side management opportunities that rely on customers' willingness to alter hourly consumption patterns.

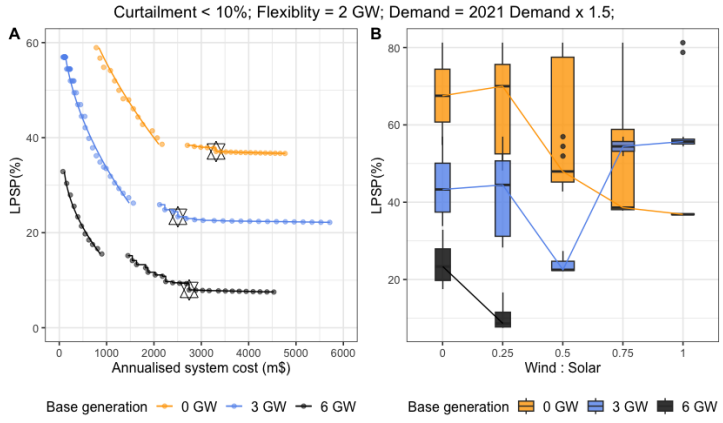

Figure 1. A) Minimum achievable Loss of Power supply Probability (LPSP) for a given system cost (Pareto frontier), and effects of different levels of base generation capacity. Reliability can be expressed as (1-LPSP). Wind and solar capacity are limited to 55 GW and 24 GW respectively, following officially assessed capacity; and curtailment is limited in these simulations to a maximum value of 10%; highest wind-solar installation on the Pareto Frontiers is shown with black star; **B)** Boxplot distributions of achievable LPSP against wind-solar ratio along the Pareto frontier for different base generation capacities; The bold lines in the middle of each box indicate the median.